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Development and assessment of a fast calibration tool for zero-dimensional combustion models in DI diesel engines

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Abstract

A fast calibration tool for the tuning of zero-dimensional combustion models has been developed and assessed on a 1.6 L Euro 6 GM diesel engine. The tool is capable of identifying the optimal set of model tuning parameters on the basis of a few combustion metrics related to heat release, as well as of peak firing pressure and indicated mean effective pressure.
The method has been assessed and validated for a real-time zero dimensional combustion model previously developed by the authors. A detailed comparison has been made between the conventional and the newly proposed calibration procedures, at both steady-state and transient-state conditions.

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Keywords: fast, calibration, combustion, diesel, modeling

1. Introduction

The increasing computational capabilities of modern ECUs (Engine Control Units) in diesel engines are offering the opportunity of implementing more and more complex model-based algorithms in order to control the combustion and pollutant formation processes in real time. The development of control-oriented real-time models that focus on these aspects [1, 2] is therefore of great interest for car manufacturers. These models can also be very useful to perform a virtual calibration of the main engine parameters in conventional [2] and hybrid powertrains [3]. Zero-

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dimensional combustion models that predict heat release rate and in-cylinder pressure are good candidates for these kind of applications, as they are computationally lowly demanding and physically consistent.

These models are usually characterized by a set of tuning parameters, which are generally identified in order to minimize the deviation between the predicted and experimental HRR and pressure curves, over a given set of engine operating conditions. However, the acquisition of the entire pressure traces of all the engine cylinders requires high memory usage. Moreover, a time-consuming post-processing phase is also required, in order to filter the high frequency components of the acquired pressure curves, as well as to derive the experimental heat release traces which are required for the tuning of the model parameters.

Modern acquisition software installed at the engine test bench usually has the capability of deriving and storing several combustion metrics in real-time, such as MFB crank angles (e.g., MFB50, that is the crank angle at which 50% of fuel mass has burnt), IMEP (Indicated Mean Effective Pressure) and PFP (Peak Firing Pressure), without the need of storing the entire in-cylinder pressure traces. This has inspired the development of a new fast calibration tool, which is capable of identifying the optimal set of model tuning parameters on the basis of a few MFB combustion metrics, as well as of PFP and IMEP.

The new calibration tool has been developed and assessed for a previously developed real-time zero-dimensional combustion model [1] developed by the authors, which is capable of predicting HRR and in-cylinder pressure on the basis of an enhanced version [4] of the accumulated fuel mass approach [5-7].

The experimental tests used for model calibration have been acquired at a dynamic test bench at GMPT-E (General Motors Powertrain Europe) and include a complete engine map as well as several full-factorial variation lists of the main engine parameters. The model performance calibrated with the fast tool has also been tested in transient conditions, over WLTP (Worldwide harmonized Light vehicles Test Procedures) mission.

A detailed comparison has been made between the conventional and the newly proposed calibration procedures.

Nomenclature

BMEP	Brake Mean Effective Pressure
IMEP	Indicated Mean Effective Pressure
K	model parameter related to combustion rate
MFB	burned fuel mass fraction metrics
n, n’	exponents of the polytropic evolution during the compression/expansion phase
PFP	Peak Firing Pressure
Q_{ch}	chemical energy release
$Q_{f,evap}$	energy associated to fuel evaporation
$Q_{ht,glob}$	global heat transfer between the charge and the walls
Q_{net}	net heat release
τ	ignition delay parameter of the model

2. Engine setup and experimental activity

The experimental tests for the calibration and validation of the models were conducted on a 1.6L Euro 6 diesel engine. The main engine technical specifications are summarized in Tab. 1.

The engine is equipped with a short-route cooled EGR system, in which the EGR valve is located upstream from the cooler. A throttle valve is installed upstream from the intake manifold and EGR junction, in order to allow high EGR rates to be obtained when the pressure drop between the exhaust and intake manifolds is not sufficient. Moreover, the EGR circuit is equipped with an EGR cooler bypass, in order to prevent EGR gases from flowing across the cooler under certain driving conditions, e.g., during cold start phases.

The test engine was instrumented with piezoresistive pressure transducers and thermocouples to measure the pressure and temperature at different locations, such as upstream and downstream from the compressor, turbine and intercooler, and in the intake manifold.

Table 1. Main engine specifications.

Engine type	Euro 6 diesel engine, 4 valves per cylinder
Displacement, compression ratio	1598 cm^3 , 16.0
Bore x stroke x rod length	79.7 mm x 80.1 mm x 135 mm
Turbocharger, Fuel injection system	VGT type, Common Rail
Specific power and torque	71 kW/l – 205 Nm/l

Thermocouples were also used to measure the temperature in each exhaust runner. Piezoelectric transducers were installed to measure the pressure time-histories in the combustion chamber.

The experimental tests were carried out on a dynamic test bench at GMPT-E, in the frame of a research project between the Politecnico di Torino and GMPT-E, pertaining to the assessment of control-oriented heat release predictive models [4]. To this aim, several tests were conducted, including:

- Full-Factorial variation tests of p_{int} (intake manifold pressure), SOI_{main} (start of injection of the main pulse), O_2 (intake oxygen concentration) and p_f (injection pressure) at several representative key-points of the NEDC. The key-points, in terms of speedxBMEP, are: 1500x2, 1500x5, 1500x8, 2000x2, 2000x5, 2000x8, 2000x12 rpmxbar. Details about the variation range of the parameters can be found in [1].
- A full engine map with baseline operating parameters.

3. Real-time zero-dimensional combustion model

The fast calibration procedure developed in this study has been applied to a previously developed real-time combustion model, which is capable of simulating the heat release rate and the in-cylinder pressure on the basis of the injection parameters and several thermodynamic quantities of the gases in the intake/exhaust manifolds. This combustion model is embedded in a complete real-time engine model [1], which is also capable of simulating engine friction and brake torque, as well as in-cylinder temperatures and NOx/soot emissions.
A synthetic description of the zero-dimensional combustion model is reported hereafter.

3.1. Chemical energy release model

The chemical energy release has been simulated on the basis of an enhanced version [4] of the baseline model presented by the authors in [7], which was based on the accumulated fuel mass approach.

The chemical energy release rate of each pilot pulse *pil,j* has been simulated using the baseline model, as follows:

$$\frac{dQ_{ch,pil,j}}{dt}(t) = K_{pil,j}[Q_{fuel,pil,j}(t-\tau_{pil,j}) - Q_{ch,pil,j}(t)] \tag{1}$$

where $K_{pil,j}$ and $\tau_{pil,j}$ are model calibration quantities related to the combustion rate and to the ignition delay, respectively, and $Q_{fuel,pil,j}$ is the chemical energy associated with the injected fuel mass.

The chemical energy release of the main pulse has instead been simulated by means of a modified formulation that was proposed in [4]:

$$\frac{dQ_{ch,main}}{dt}(t) = K_{1,main}[Q_{fuel,main}(t-\tau_{main}) - Q_{ch,main}(t)] + K_{2,main}\frac{dQ_{fuel,main}(t-\tau_{main})}{dt} \tag{2}$$

The formulation proposed in Eq. (2) needs an additional calibration parameter with respect to the baseline approach of Eq. (1) (i.e., $K_{2,main}$).

For each injection pulse j, the chemical energy Q_{fuel} associated to the injected fuel quantity is defined as follows:

$$Q_{fuel,j}(t) = \int_{t_{SOI,j}}^{t} \dot{m}_{f,inj}(t) H_L dt \quad for \quad t \le t_{EOI,j}; \qquad Q_{fuel,j}(t) = \int_{t_{SOI,j}}^{t_{EOI,j}} \dot{m}_{f,inj}(t) H_L dt \quad for \quad t > t_{EOI,j} \tag{3}$$

where t_{SOI} is the start of the injection time, t_{EOI} the end of the injection time, H_L the lower heating value of the fuel and $\dot{m}_{f,inj}$ the fuel mass injection rate.

The total chemical energy release is given by the sum of the contributions of all the injection pulses:

3.2. In-cylinder pressure model

The first step to simulate the in-cylinder pressure involves the estimation of the net energy release, starting from the chemical release. To this purpose, it is necessary to account for heat transfer and fuel evaporation heat effects [7]. The net heat release is derived from the chemical release according to the following formulation [7]:

$$Q_{net}^{SOC} \cong Q_{ch} \frac{m_{f,inj} H_L - Q_{ht,glob}}{m_{f,inj} H_L} \tag{4}$$

$$Q_{net}^{SOI} \cong Q_{net}^{SOC} - Q_{f,evap} \tag{5}$$

where $Q_{net}{}^{SOC}$ and $Q_{net}{}^{SOI}$ indicate the net energy release calculated from SOC or SOI, respectively, $Q_{f,evap}$ and $Q_{ht,glob}$ indicate the fuel evaporation heat from SOI to SOC (J) and the heat globally exchanged between the charge and the walls over the combustion cycle (J), and $m_{j,inj}$ is the total injected fuel mass per cycle/cylinder.

The in-chamber pressure was evaluated during the combustion interval using a single-zone model [8]:

$$dp = \left(\frac{\gamma - 1}{V} \right) \left(dQ_{net} - \frac{\gamma}{\gamma - 1} pdV \right) \tag{6}$$

where the isentropic coefficient $\gamma = c_p / c_v$ was set to be constant and equal to 1.37.

Polytropic evolutions were assumed to calculate the in-cylinder pressure during the compression and expansion phases, with exponents n and n', respectively:

$$pV^n = const; \qquad pV^{n'} = const \tag{7}$$

The in-chamber pressure at IVC (Intake Valve Closure), that is, the starting condition, was correlated to the pressure in the intake manifold p_{int}, using a correction factor Δp_{int}, as follows:

$$p_{IVC} = p_{int} + \Delta p_{int} \tag{8}$$

4. Conventional calibration procedure

The main calibration parameters of the heat release model (K_j, τ_j) and of the pressure model ($Q_{f,evap}$, $Q_{ht,glob}$, n, n', Δp_{int}) need to be properly tuned before the model implementation. The tuning conventional calibration procedure generally requires the acquisition of the in-cylinder pressure trace in at least one of the cylinders. In particular, a set of engine operating conditions is chosen for model tuning. For each engine point, first the experimental heat release rate is derived using a single zone approach [8]. Then, the heat release model parameters K_j and τ_j are properly tuned in order to obtain the best matching between the predicted and experimental chemical energy release curves. Finally physically-consistent correlations are identified for K_j and τ_j as a function of properly selected engine variables, on the basis of the optimal values identified for each engine point. A similar procedure is followed for the tuning of the in-cylinder pressure model. In particular, the experimental values of the global heat transfer $Q_{ht,glob}$ and fuel evaporation heat $Q_{ht,glob}$ can be derived from the experimental net heat release trace (see [7]), while the experimental values of the n, n' and Δp_{int} can parameters can be derived directly from the experimental in-cylinder pressure trace (see again [7]). In the end, physically consistent correlations are identified also for these tuning parameters.

The correlations of the model parameters using the conventional calibration procedure are reported in [1].

5. Fast calibration procedure

The fast calibration tool proposed in this paper is capable of identifying the optimal set of model tuning parameters without the acquisition of the entire in-cylinder pressure traces.

In particular, the heat release model is tuned on the basis of a few combustion metrics related to the burned fuel mass fraction (MFB points), while the in-cylinder pressure model is tuned just on the basis of PFP and IMEP quantities. These metrics are usually automatically derived and stored in real-time by the acquisition software installed at the engine test bench, without the need of acquiring the whole in-cylinder pressure traces, which are highly memory consuming. The new calibration procedure, which is described hereafter, makes the model tuning much faster than the conventional method.

With reference to the chemical energy release model, the optimal values of the K_j and τ_j parameters, for a given engine operating condition, are identified by minimizing the error between the predicted and experimental MFB points. The minimum number of MFB metrics to be used for an accurate model calibration, as well as the selection of the metrics themselves, is not obvious. To this end, a detailed sensitivity analysis has been carried out. First, 10 discrete values of MFB have been considered (i.e., MFB1, MFB10, MFB20, …, MFB90). Then, the K_j and τ_j model parameters were tuned considering a variable number of MFB metrics (from 4 to 10). For a given number of MFB metrics used for tuning, all the possible combinations of the 10 discrete MFB metrics have been investigated, and for each combination the root mean square error (RMSE) between the predicted and experimental values of the metrics has been evaluated over the entire dataset of engine calibration points. This procedure has allowed to identify what are the best metrics to be selected if the calibration is carried out with a given number of MFB points (i.e., the combination which leads to the lowest RMSE over the entire calibration dataset is selected). Finally, the RMSE values obtained with different numbers of MFB points have been compared with each other, in order to identify which is the minimum number of MFB metrics that allows an accurate model calibration to be obtained.

It should be noted that, from a theoretical point of view, the minimum number of MFB metrics to be used for tuning depends on the number of K_j and τ_j coefficients to be identified, which in turn depends on the number of injection pulses. Three parameters are required for the main pulse (see Eq. (2)), and two additional parameters for each additional injection pulse (see Eq. (1)). However, the main injection pulse in general has a predominant contribution on the heat release shape, compared to the other pulses. Therefore, the minimum investigated number of MFB metrics has been selected as 3, so as to be able to tune at least the $K_{1,main}$, $K_{2,main}$ and τ_{main} parameters of Eq. (2). In case other pulses are present, suitable constant values are adopted for the related K and τ parameters. From this analysis, it has been found that at least 5 MFB metrics are needed to obtain an accurate prediction of the heat release profile, and these metrics are MFB1, MFB10, MFB30, MFB50 and MFB80. The MFB1 metric is needed in order to correctly take into account the effects of pilot injections.

With reference to the in-cylinder pressure model calibration, five tuning parameters ($Q_{f,evap}$, $Q_{ht,glob}$, n, n', Δp_{int}) should be identified for a given engine operating condition, therefore a minimum number of 5 metrics would be required. However, it was shown in [7] that $Q_{ht,glob}$ and n are the parameters with most influence on the model outcomes. Therefore, only two pressure metrics (i.e., PFP and IMEP) have been considered for the tuning of $Q_{ht,glob}$ and n, while constant values were adopted for the $Q_{f,evap}$, n' and Δp_{int} parameters, which were selected on the basis of experience. Figure 1 reports, for three different operating conditions (NxBMEP) an example of predicted vs. experimental curves of Q_{ch} and p adopting the fast and conventional calibration procedures. It can be seen that the curves obtained using the fast calibration procedure are very near to those obtained with the conventional one for all the considered cases. Once the model calibration parameters have been identified for the entire dataset of calibration points, physically-consistent correlations (not reported here for the sake of brevity) have then been identified for each parameter, in a similar way as those reported in [1].

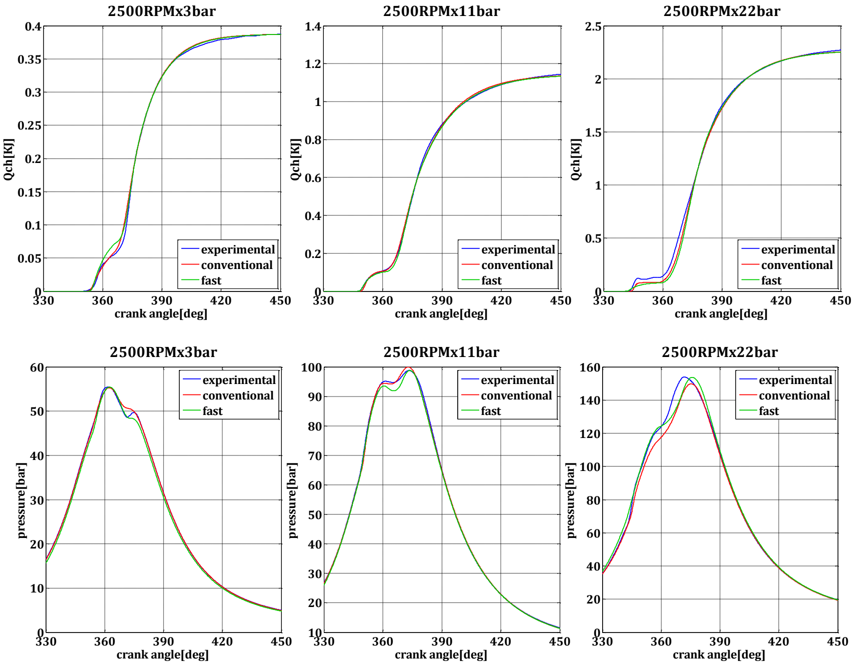

Fig. 1. Predicted vs. experimental Q_{ch} and p curves adopting the fast and conventional calibration procedures.

6. Results and discussion

Figure 2 shows a comparison between the predicted vs. experimental MFB50 values using the fast calibration procedure (Fig. 2a) and the conventional calibration procedure (Fig. 2d).

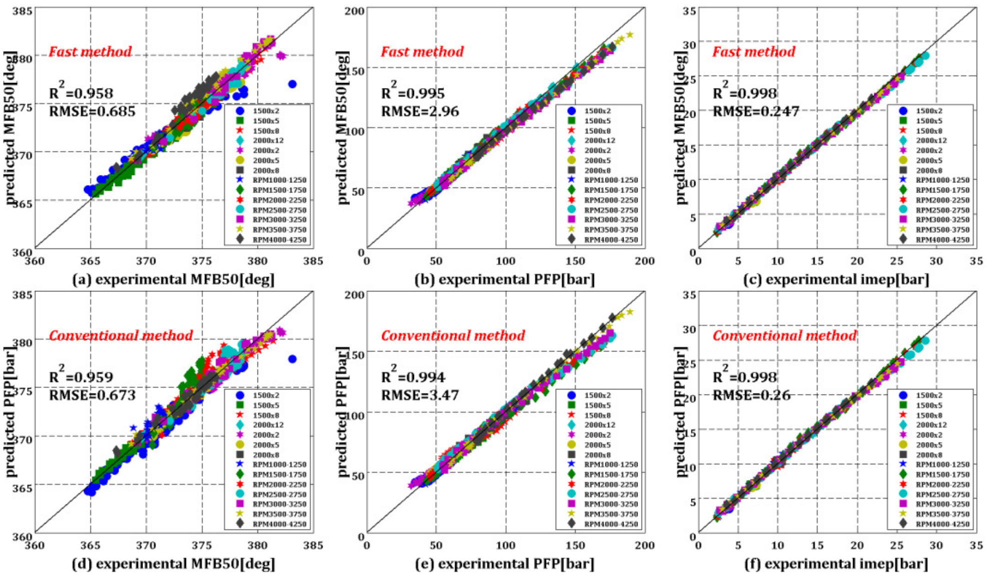

Fig. 2. Predicted vs. experimental values of MFB50, PFP, IMEP adopting the fast and conventional calibration procedures.

MFB50 has been selected as it is a commonly used combustion metric for control purposes, therefore an accurate estimation is desirable. In the same figure, a comparison between the predicted and experimental values of PFP and IMEP, obtained with the model tuned using the fast calibration procedure (Fig. 2b, 2c) and the conventional calibration procedure (Fig. 2e, 2f) is provided. The squared correlation coefficient (R^2) and the root mean square of the error (RMSE) are also reported. It can be seen that, at steady-state conditions, the accuracy of the model calibrated on the basis of the fast method is very similar to that of the model calibrated using the conventional method.

Table 2 reports, for the two calibration procedures, a comparison between RMSE of MFB50, PFP and IMEP, as well as SSD (sum of square differences) between the predicted and experimental curves of the burned mass fraction x_b and of the in-cylinder pressure. The x_b curve was obtained by normalizing the Q_{ch} trace. The SSD is an indicator of the accuracy in the prediction of the shape of the predicted heat release and pressure curves. It can be seen that the accuracy obtained using the fast calibration approach is very similar to that of the conventional one.

Table 2. Comparison between the RMSE and SSD values using the conventional and fast calibration procedures.

	Fast calibration procedure	Conventional calibration procedure
RMSE MFB50(deg), PFP(bar), IMEP (bar)	0.67, 3.47, 0.26	0.69, 2.96, 0.24
SSD x_b(-), in-cylinder pressure (bar)	0.61, 1.04	0.75, 0.84

Finally, Figure 3 shows a comparison between the predicted and experimental values of the MFB50, PFP and IMEP obtained by the model calibrated with the conventional and fast calibration procedures over the WLTP. The RMSE values are also reported. It can be seen how the fast calibration procedure leads to a very similar accuracy than that of the conventional procedure, also over transient conditions.

7. Conclusion

A fast calibration tool for the tuning of zero-dimensional combustion models has been developed and assessed on a 1.6 L Euro 6 GM diesel engine. The tool is capable of identifying the optimal set of model calibration parameters on the basis of a few combustion metrics related to heat release, as well as of the measured values of peak firing pressure (PFP) and indicated mean effective pressure (IMEP). These metrics are usually derived and stored in real-time at the engine test bench during the experimental activity, without the need of storing the entire in-cylinder pressure traces for all the acquired experimental tests.

The method has been assessed and validated for a real-time zero dimensional combustion model previously developed by the authors, which is based on the accumulated fuel mass approach.

From this analysis, it has been found that at least 5 MFB metrics are needed to obtain an accurate prediction of the heat release profile, and these metrics are MFB1, MFB10, MFB30, MFB50 and MFB80. The MFB1 metric is needed in order to correctly take into account the effects of pilot injections. Instead, IMEP and PFP have been selected as the most appropriate metrics to correctly tune the parameters of the in-cylinder pressure model.

It was found that the proposed fast calibration procedure leads to a very similar accuracy to that obtained using the standard calibration procedures, at both steady-state and transient conditions over WLTP.

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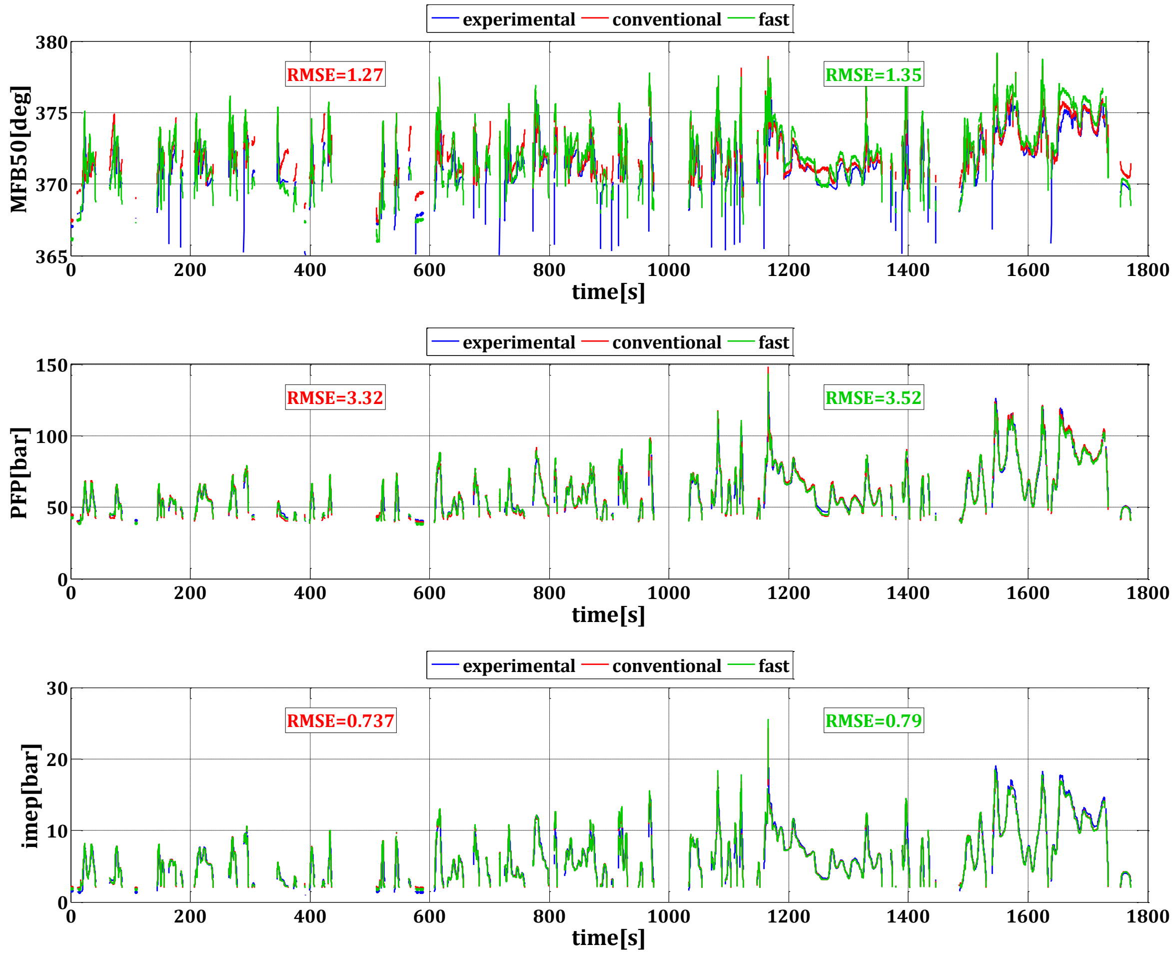

Fig. 3. Predicted vs. experimental values of MFB50, PFP, IMEP over WLTP for the conventional and fast calibration procedures

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